Heavy new physics in top production and decay

C. Degrande
UIUC

Snowmass Energy Frontier Workshop

Brookhaven, April 3-6

Plan

- Introduction to EFT
- Top decay
- Top pair production
- Same sign top pair production
- Concluding remarks

Effective Field Theory

- Energy of the process (E) « New Physics scale (Λ)
- Expansion in $E/\Lambda \ll 1$
- Lagrangian : $\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$
- Operators with the lowest dimension have the largest effects
- One theory : fixed coefficients
- Free coefficients = Model Independent

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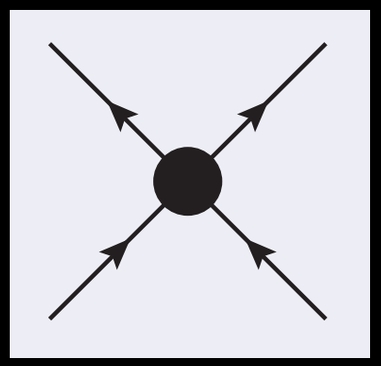
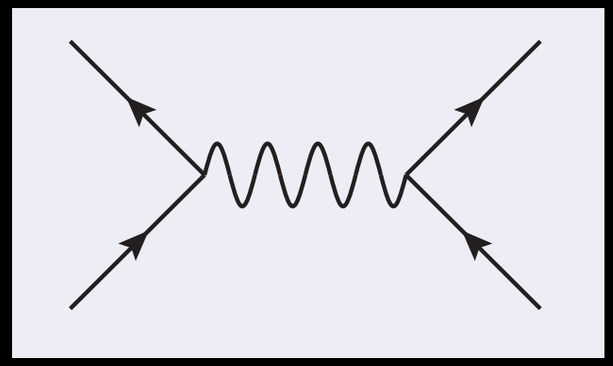
Model Independent Searches

EFT



"Global" shape effects

Resonance



Peak in the invariant mass

Λ

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Model Independent Searches

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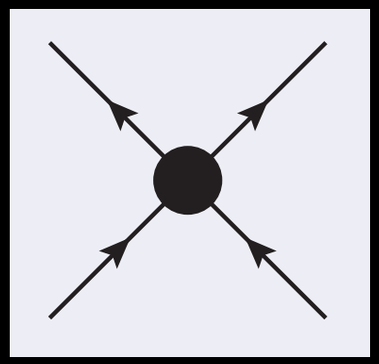
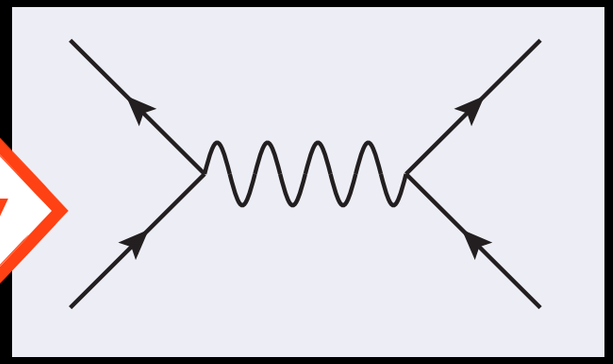


Complementary



"Global" shape effects

Peak in the invariant mass

Λ

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Building the operators

- SM symmetries including B and L
- Dimension-six operators
- CP
- Interference only:

$$|M|^2 = |M_{SM}|^2 + 2\Re\left(M_{SM}M^*_{dim6}\right) + \mathcal{O}\left(\Lambda^{-4}\right)$$

(SM-like) Top decay

$t \to bW$

$$\mathcal{O}_{\phi q}^{(3)} = i\left(\phi^\dagger \tau^i D_\mu \phi\right)\left(\bar{Q}\gamma^\mu \tau^i Q\right) + h.c.$$
$$\mathcal{O}_{tW} = \bar{Q}\sigma_{\mu\nu}\tau^i t\tilde{\phi}W_i^{\mu\nu}.$$

C. Zhang, S Willenbrock, PRD83, 034008

$t \to bl\nu_l$

$$\mathcal{O}_{ql}^{(3)} = \left(\bar{Q}\gamma^\mu \tau^i Q\right)\left(\bar{l}\gamma_\mu \tau^i l\right)$$

J.A. Aguilar-Saavedra, NPB843, 683

+ one four-fermion operator for the hadronic decay

$$\frac{1}{2}\Sigma|M|^2 = \frac{V_{tb}^2 g^4 u(m_t^2-u)}{2(s-m_W^2)^2}\left(1+2\frac{C_{\phi q}^{(3)}v^2}{V_{tb}\Lambda^2}\right) + \frac{4\sqrt{2}\mathrm{Re}C_{tW}V_{tb}m_t m_W}{\Lambda^2}\frac{g^2 su}{(s-m_W^2)^2}$$
$$+\frac{4C_{ql}^{(3)}}{\Lambda^2}\frac{g^2 u(m_t^2-u)}{s-m_W^2} + \mathcal{O}\left(\Lambda^{-4}\right)$$

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Width and W helicities

$$\frac{\Gamma\left(t \to be^{+}\nu_e\right)}{GeV} = 0.1541 + \left[0.019\frac{C^{(3)}_{\phi q}}{\Lambda^2} + 0.026\frac{C_{tW}}{\Lambda^2} + 0\frac{C^{(3)}_{ql}}{\Lambda^2}\right]\mathrm{TeV}^2$$

$$\left.\begin{aligned} \frac{\Gamma_t}{GeV} = \Gamma_{SM} + \left[0.17\frac{C^{(3)}_{\phi q}}{\Lambda^2} + 0.23\frac{C_{tW}}{\Lambda^2}\right]\mathrm{TeV}^2 \\ \Gamma^{*}_{meas} = 2^{+0.47}_{-0.43}\,\mathrm{GeV} \\ \Gamma^{**}_{SM} = 1.33\,\mathrm{GeV} \end{aligned}\right\} \frac{C^{(3)}_{\phi q}}{\Lambda^2} + 1.35\frac{C_{tW}}{\Lambda^2} = 4^{+2.8}_{-2.5}\mathrm{TeV}^{-2}$$

* D0, PRD85, 091104
** M.Jezabek and J.H. Kuhn, NPB314,1

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{8}(1+\cos\theta)^2 F_R + \frac{3}{8}(1-\cos\theta)^2 F_L + \frac{3}{4}\sin^2\theta F_0$$

$$\begin{aligned} F_0 &= \frac{m_t^2}{m_t^2+2m_W^2} - \frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2} \\ F_L &= \frac{2m_W^2}{m_t^2+2m_W^2} + \frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2} \\ F_R &= 0 \end{aligned}$$

$$\left.\begin{aligned} F_0^{SM\,*} = 0.687 \pm 5 \\ F_0^{meas\,**} = 0.66 \pm 5 \end{aligned}\right\} \frac{C_{tW}}{\Lambda^2} = 0.44 \pm 0.9\mathrm{TeV}^{-2}$$

* A.Czarnecki, J. G. Korner, J. H. Piclum PRD81, 111503
**Atlas,JHEP1206(2012)088

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Leptons invariant mass

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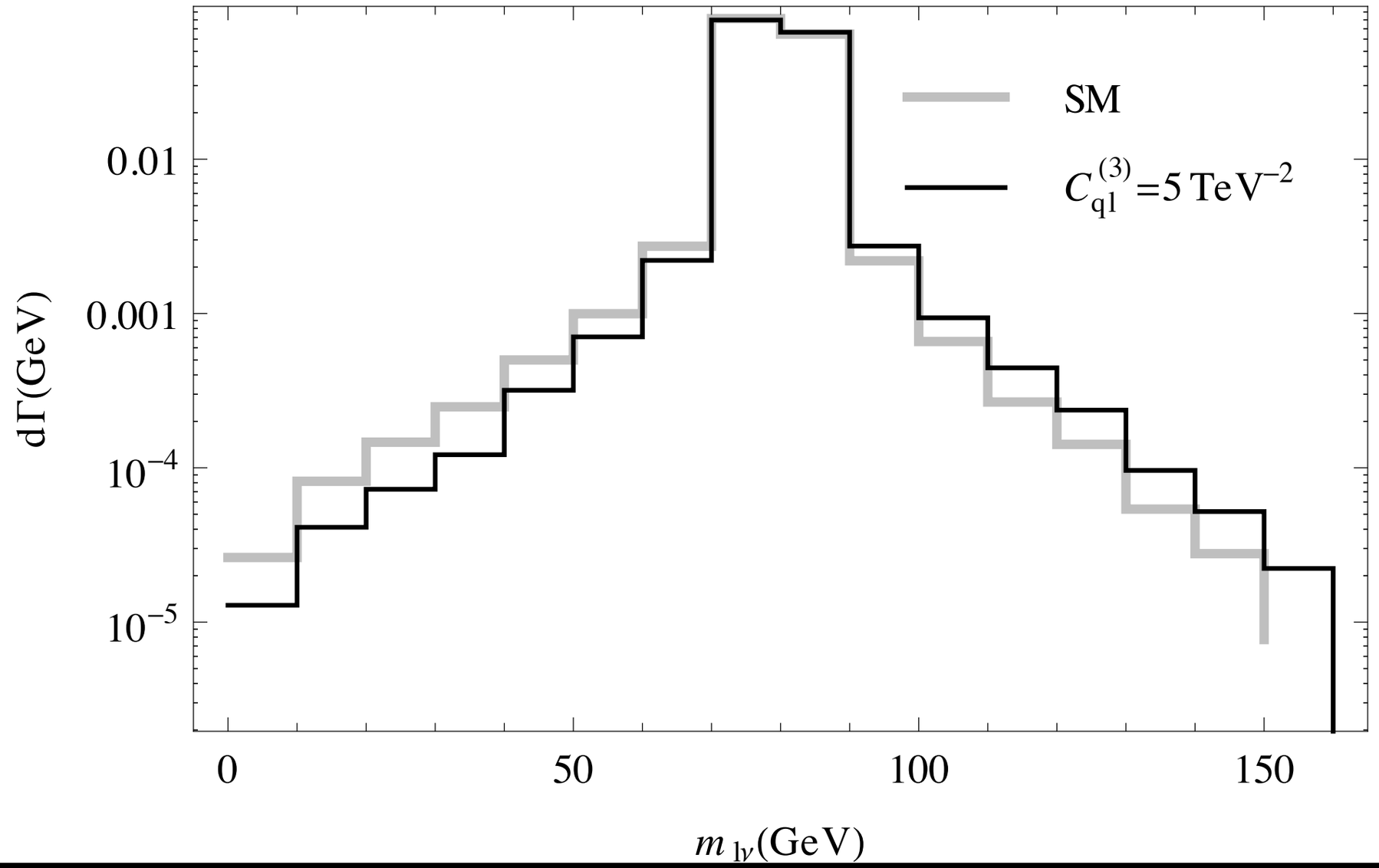

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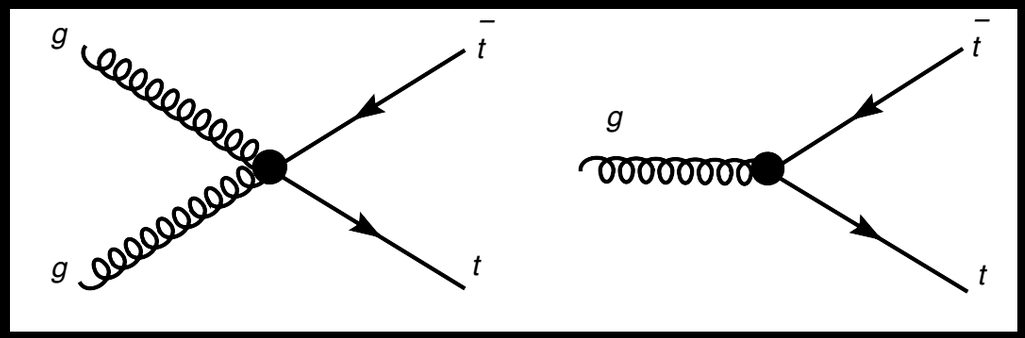
Top pair production

$$\mathcal{O}_{hG} = \bar{Q}\sigma_{\mu\nu}T^a t\tilde{\phi}G_a^{\mu\nu}$$



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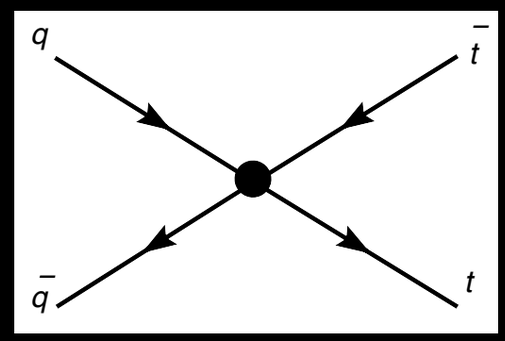

C.D., J.-M. Gerard, C. Grojean, F. Maltoni, G. Servant, JHEP 1103 (2011) 125

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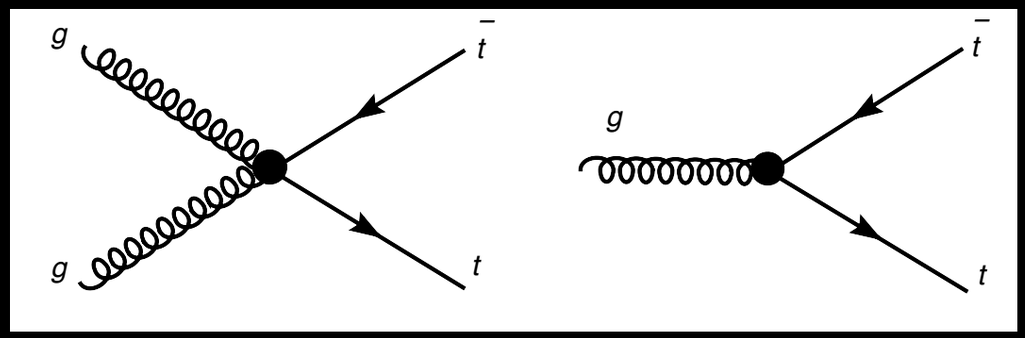

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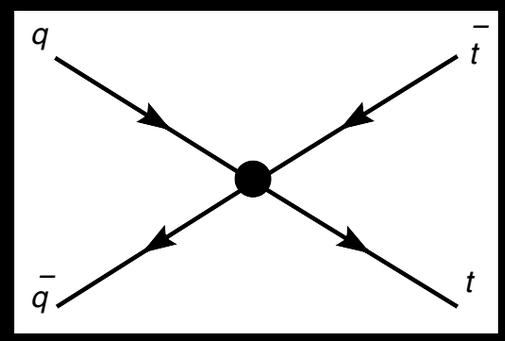

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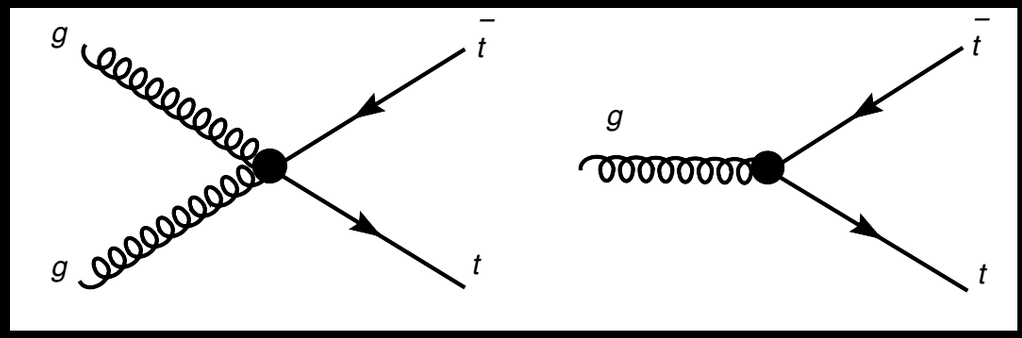

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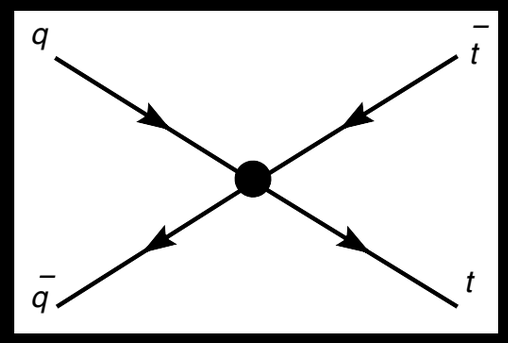

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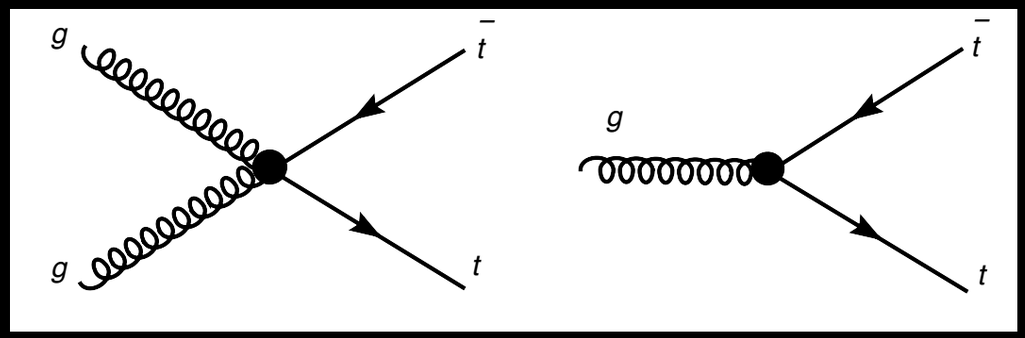

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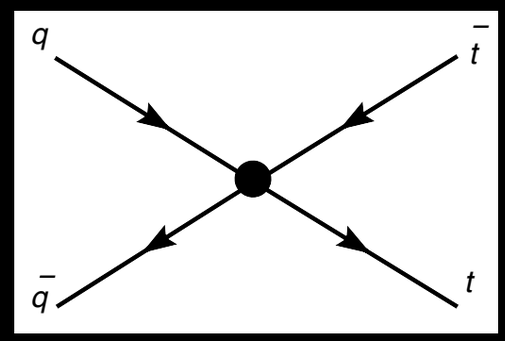

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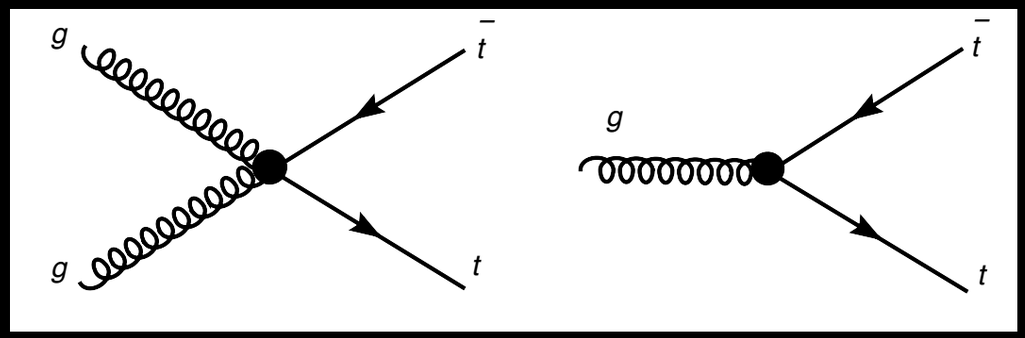

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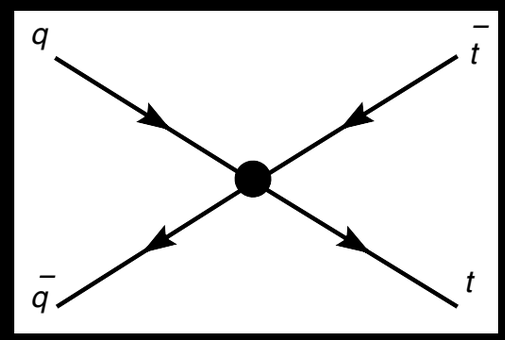

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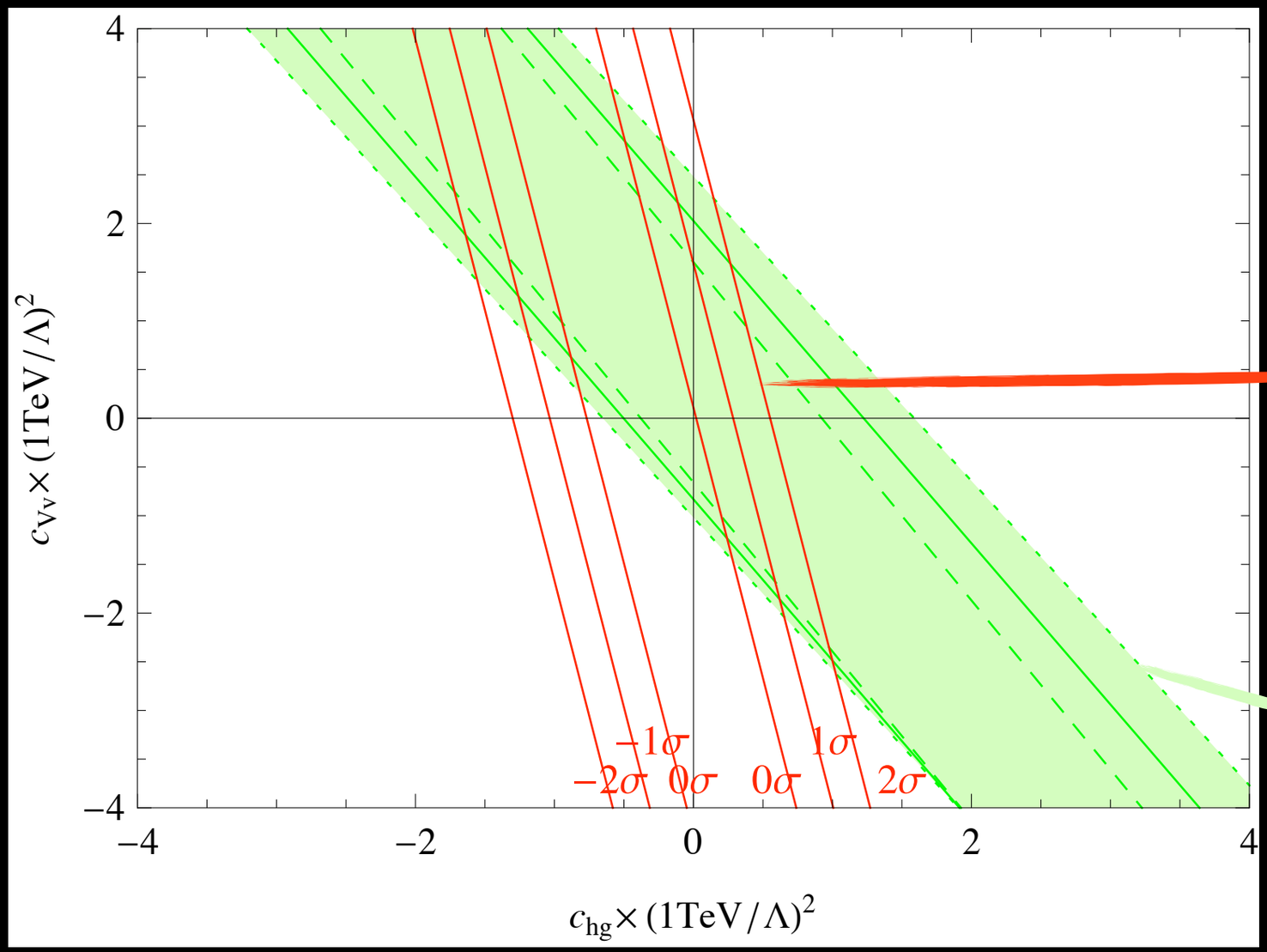
Total cross-section

NNLO+NNLL, M. Czakon, P. Fiedler and A. Mitov, arXiv:1303.6254

$c_{Vv} = c_{Rv} + c_{Lv}$



CMS, 7TeV
arXiv : 1208.2671 ,
161.9±2.5±5.1±3.6pb^{-1}

Tevatron 09/2012
Combination
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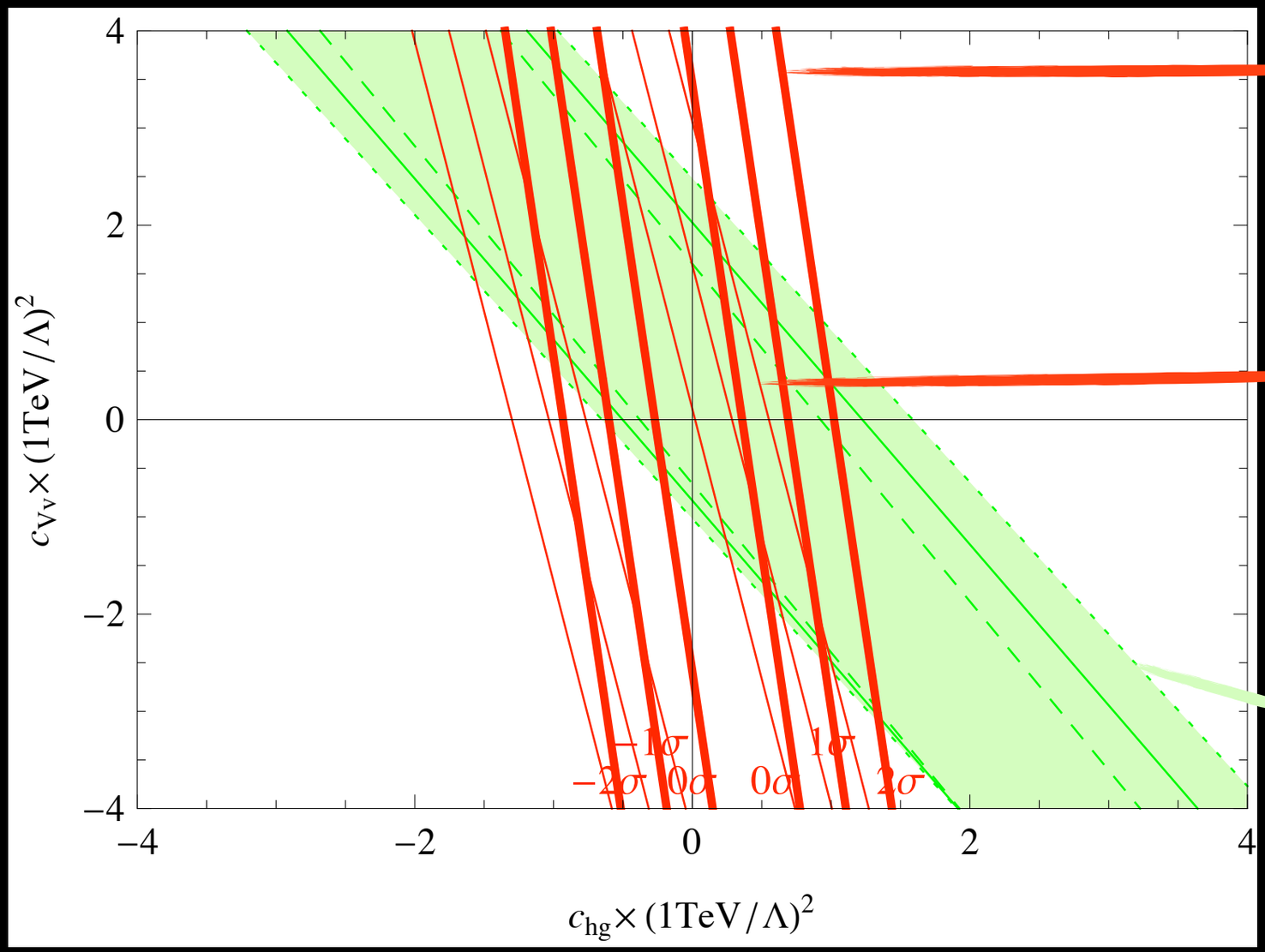

LHC, 14TeV
SM±5%

CMS, 7TeV
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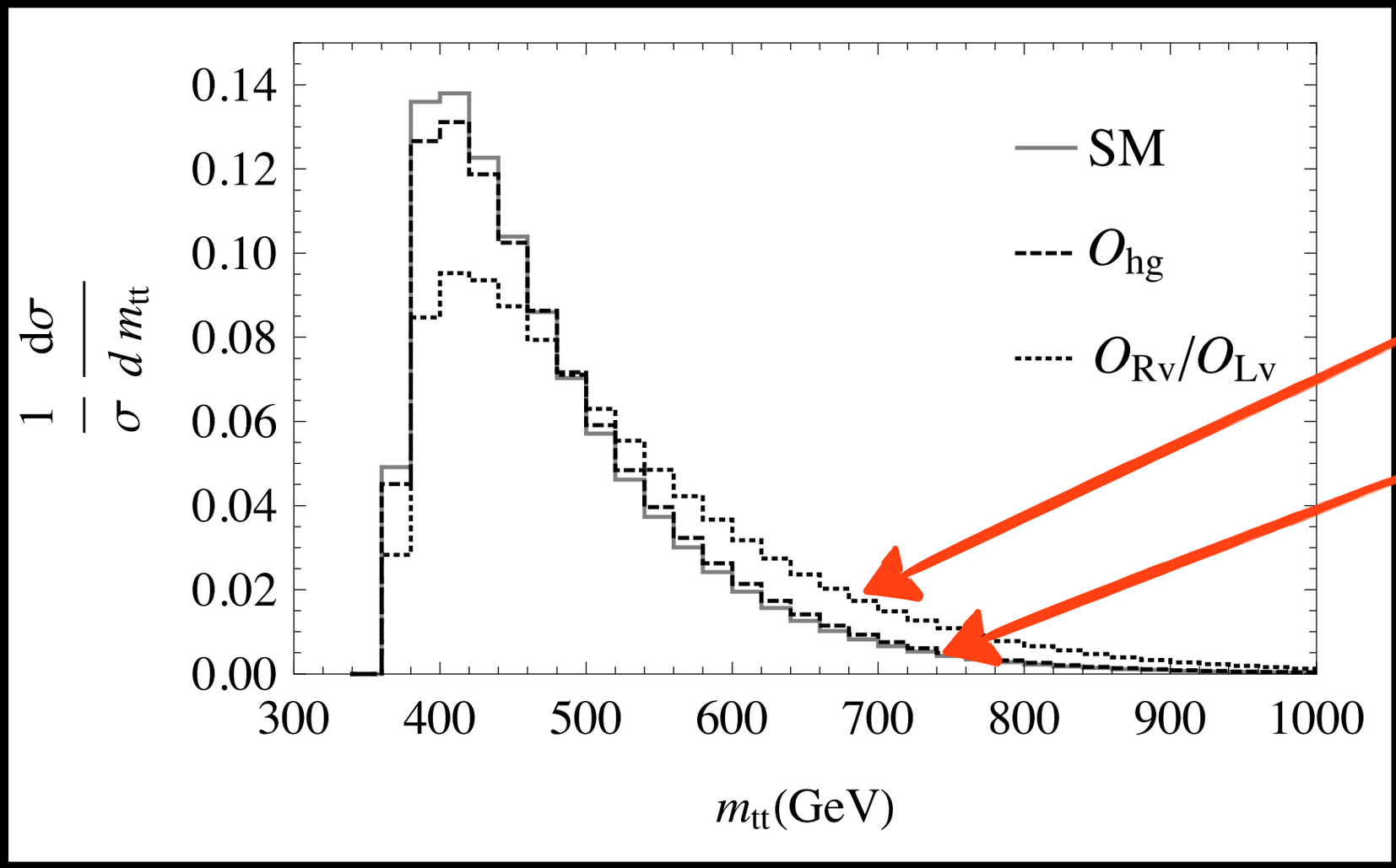
Invariant mass



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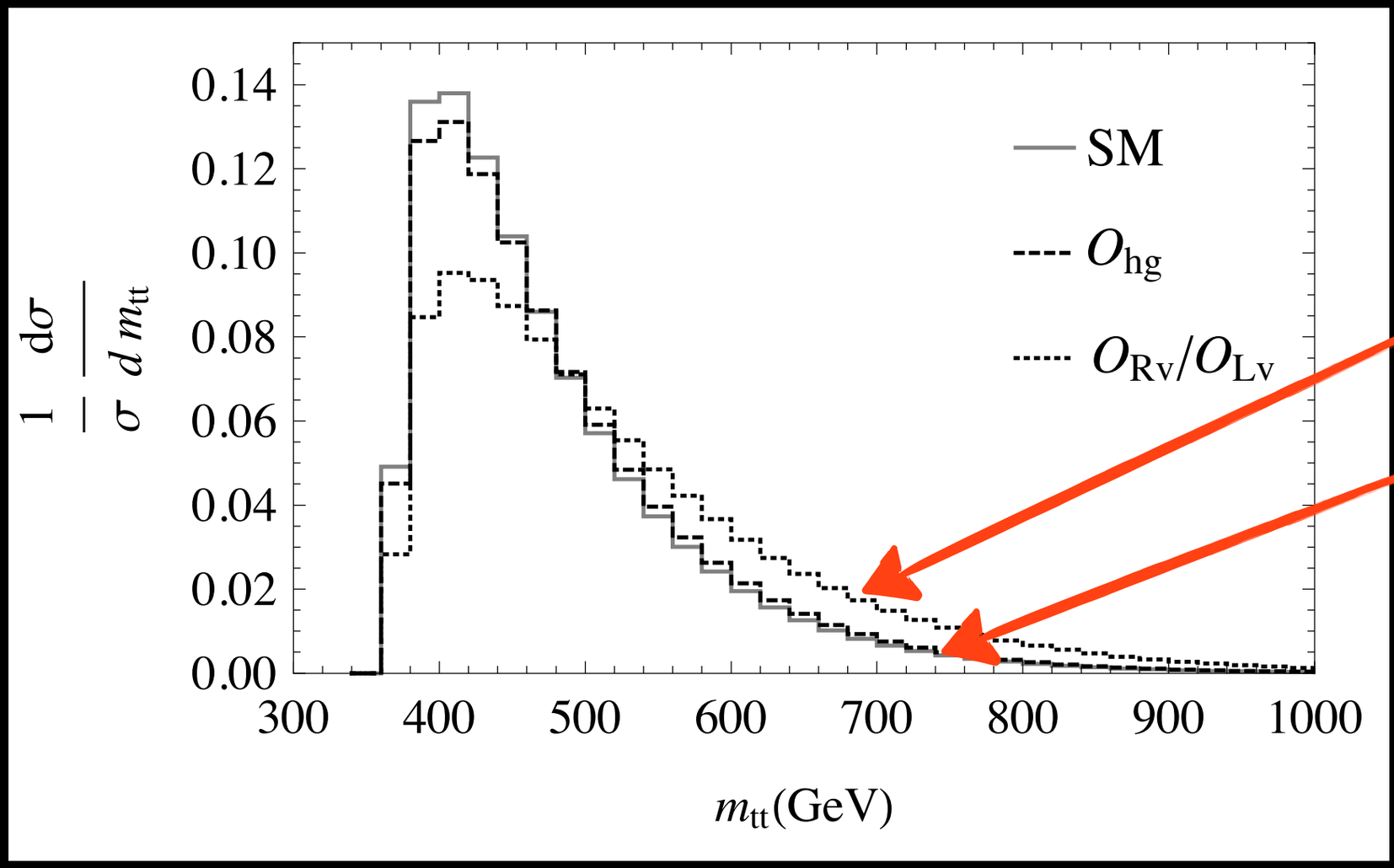

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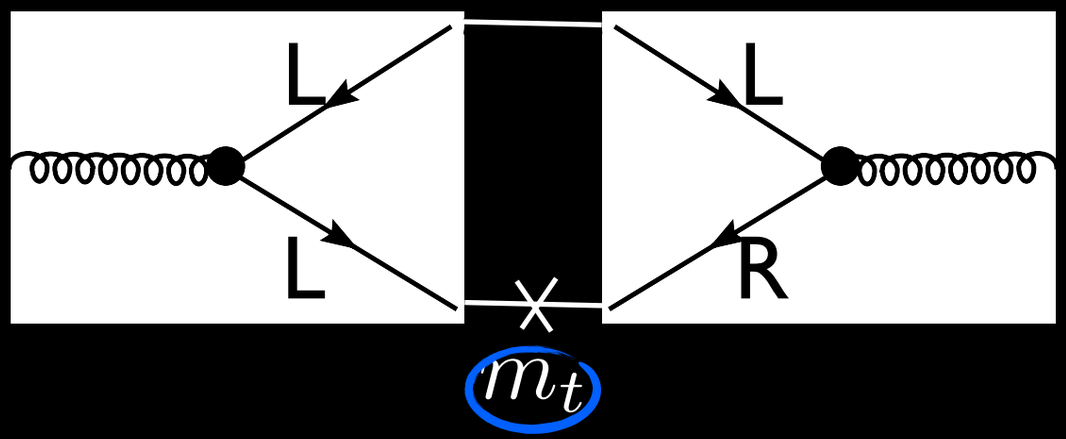

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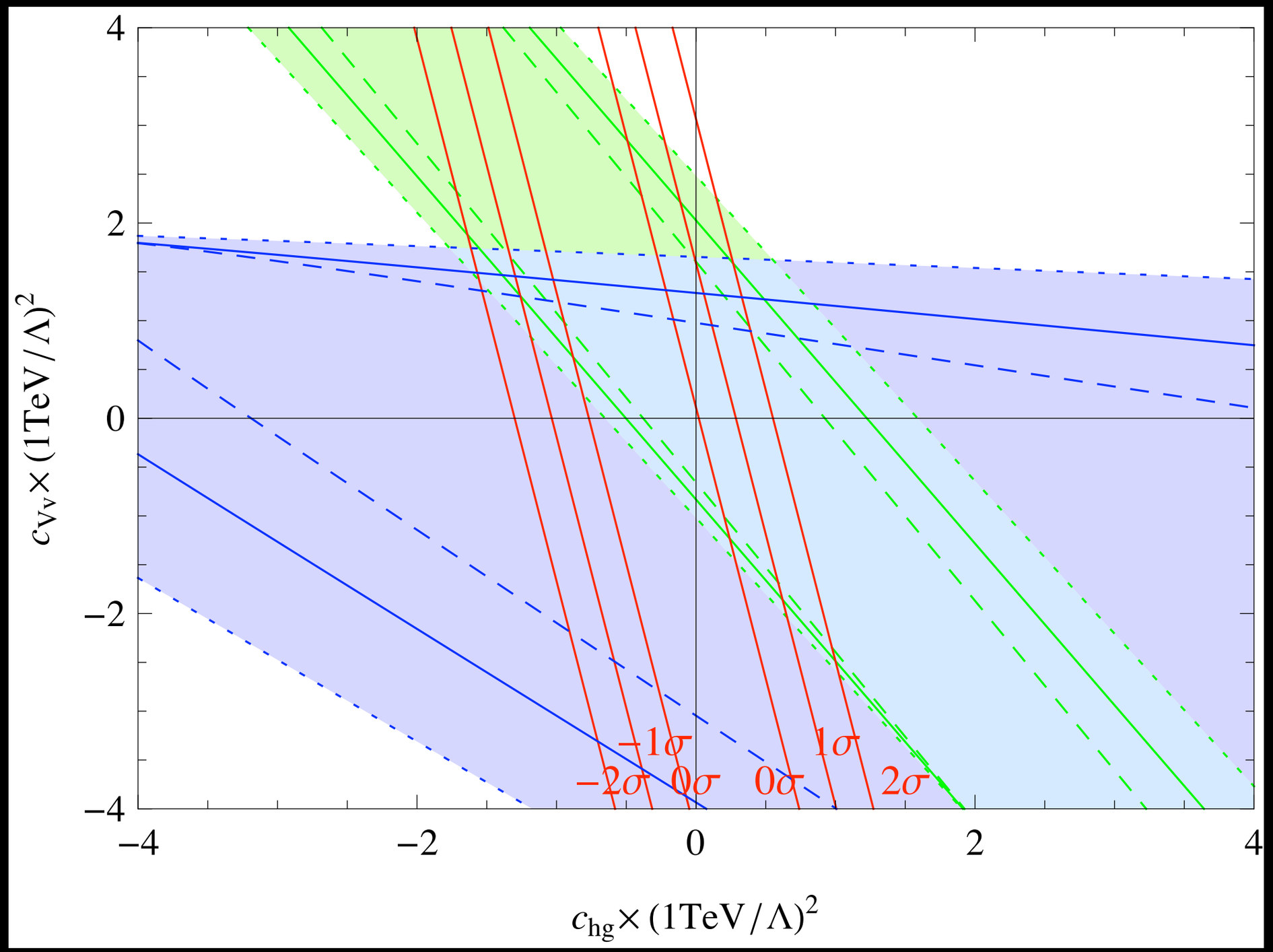

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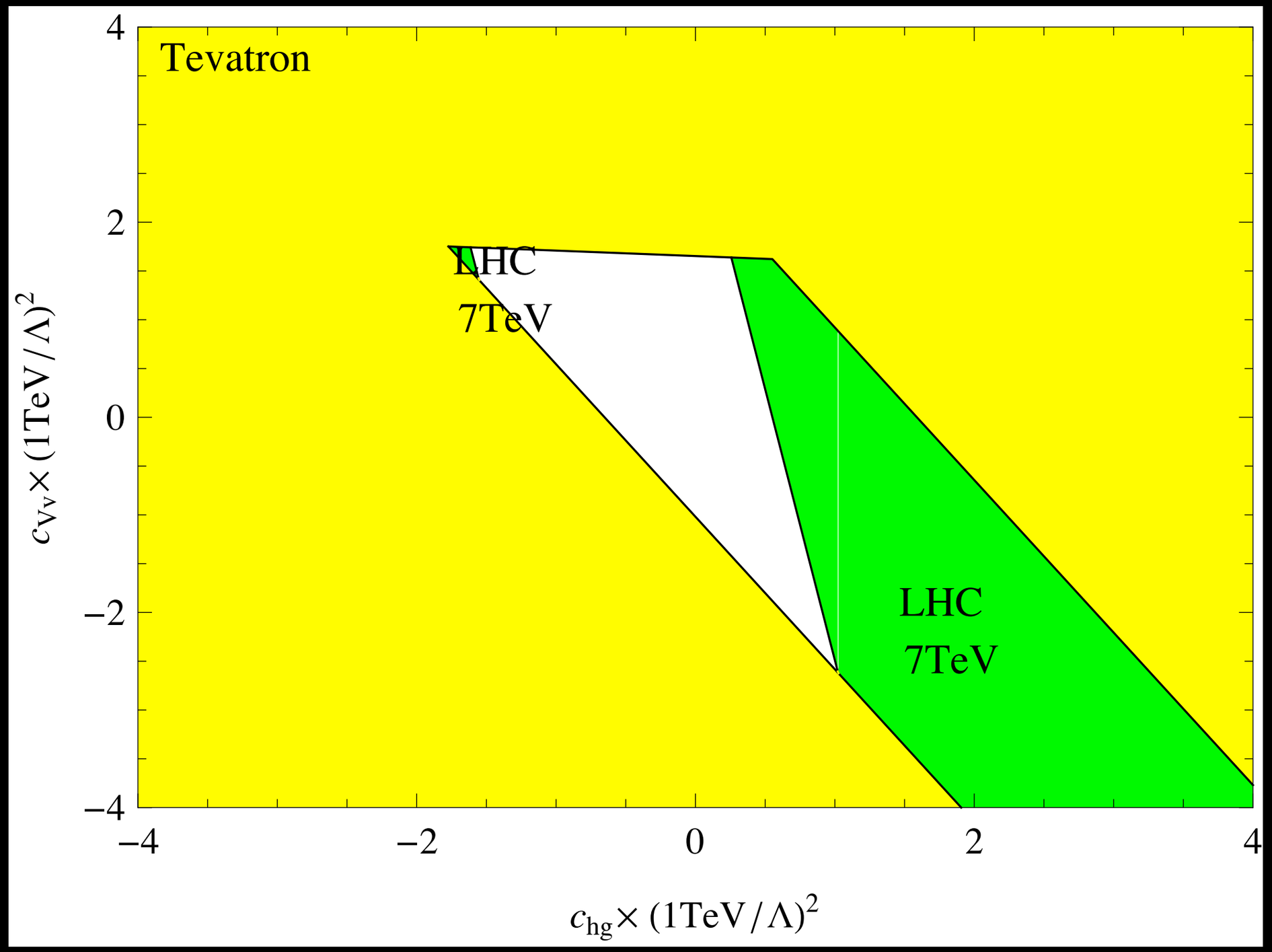

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FB asymmetry

$$A_{FB}^{obs} = 0.162 \pm 0.047$$

$$A_{FB}^{SM} = 0.066 \pm 0.007$$

$$c_{Aa} = c_{Ra} - c_{La}$$

$$\delta A_{FB} = 0.047^{+0.016}_{-0.011} c_{Aa} \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 \Rightarrow c_{Aa} \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 = 2.04^{+2.12}_{-1.38} \text{TeV}^{-2}$$

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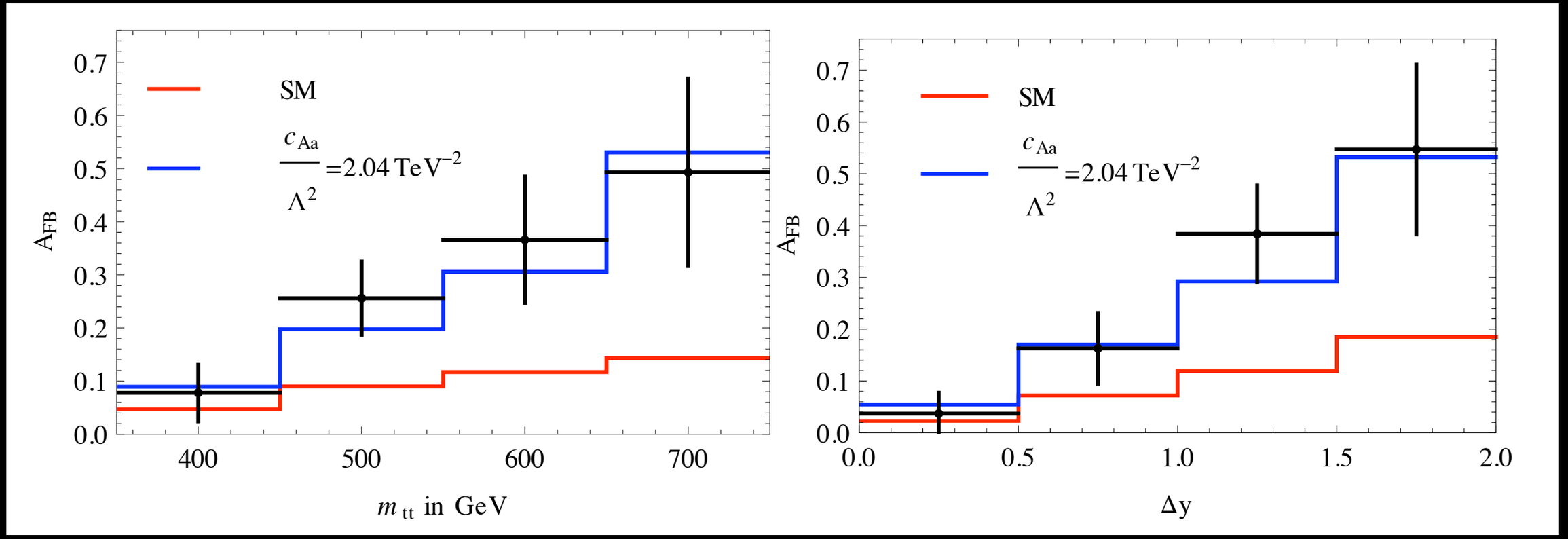

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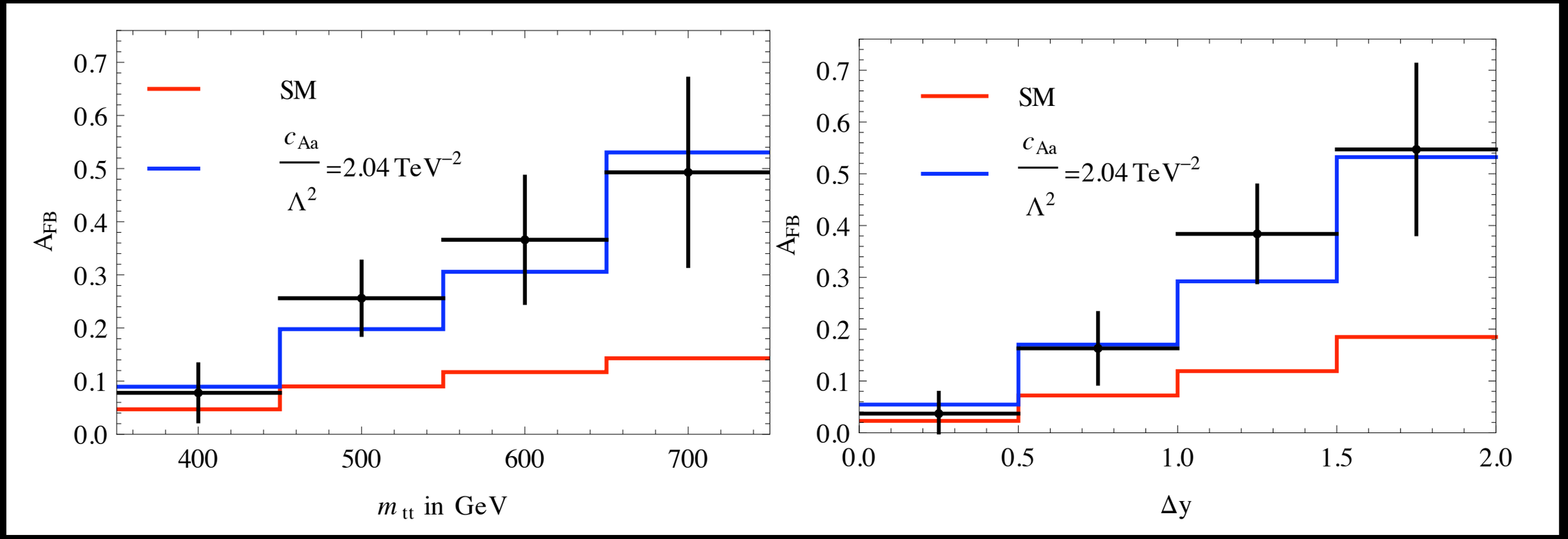

LHC Charge Asymmetry: $c_{Aa} \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 = -1.3^{+2.8}_{-1.3} \text{TeV}^{-2}$

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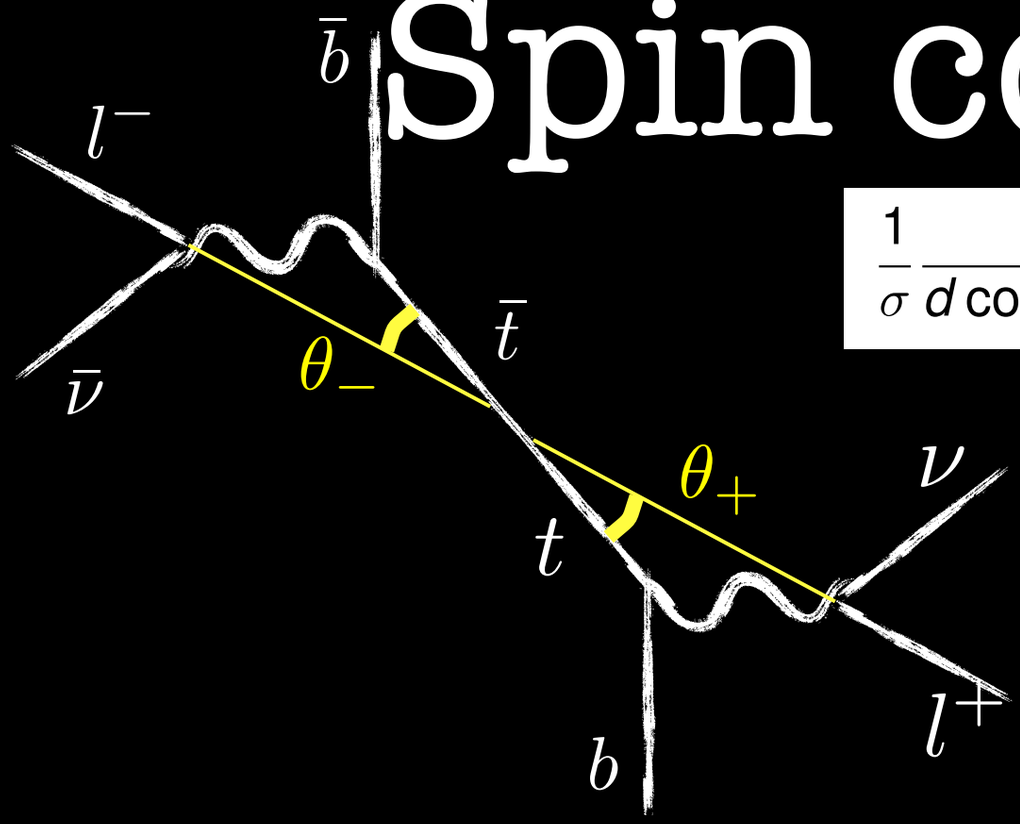
Spin correlations

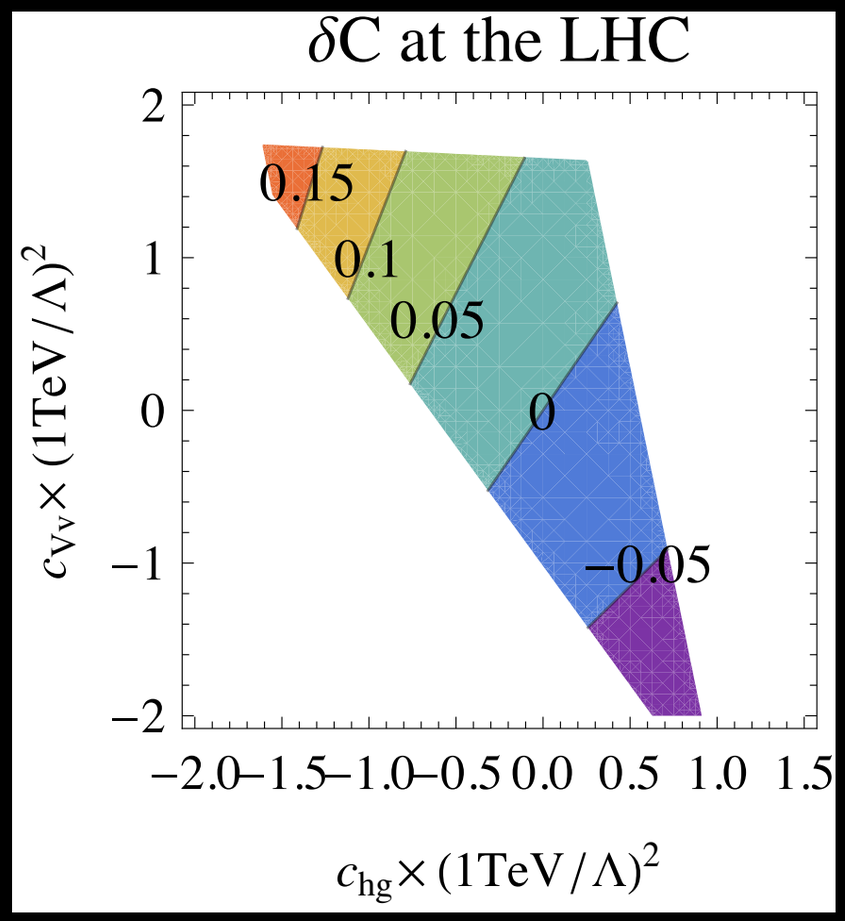


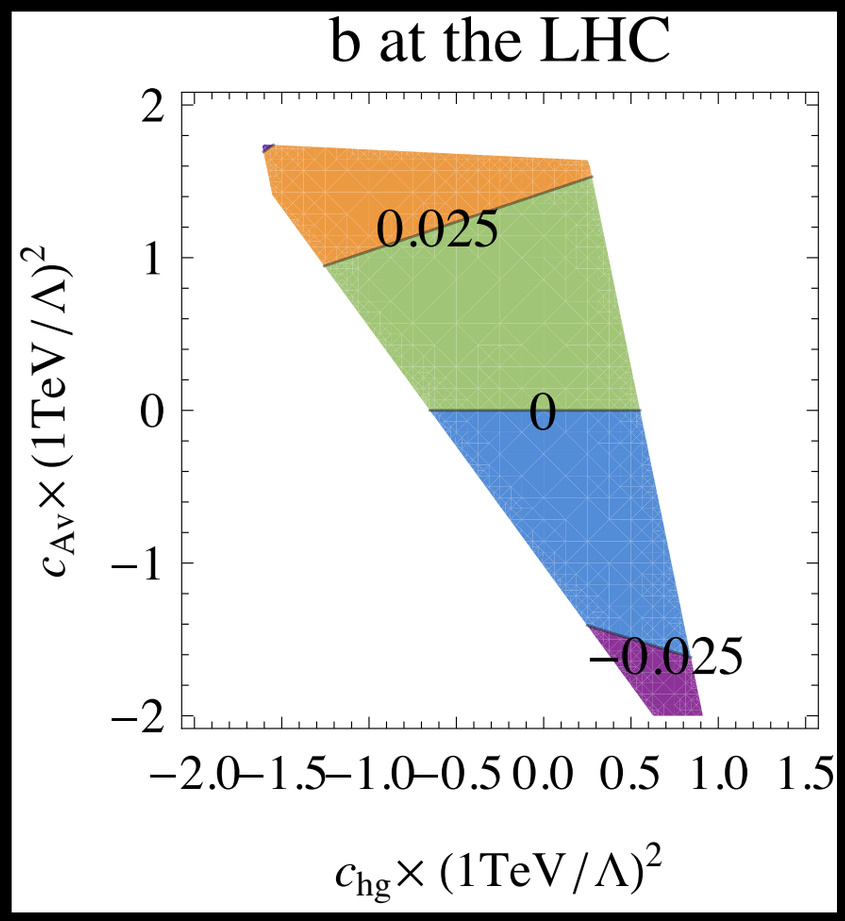
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + C\cos\theta_+\cos\theta_- + b_+\cos\theta_+ + b_-\cos\theta_-\right)$$

$$C = \frac{1}{\sigma}\left(\sigma_{LR} + \sigma_{RL} - \sigma_{RR} - \sigma_{LL}\right)$$

$$b_+ = \frac{1}{\sigma}\left(\sigma_{RL} - \sigma_{LR} + \sigma_{RR} - \sigma_{LL}\right)$$

$$b_- = \frac{1}{\sigma}\left(\sigma_{RL} - \sigma_{LR} - \sigma_{RR} + \sigma_{LL}\right)$$





$c_{Av} = c_{Rv} - c_{Lv}$

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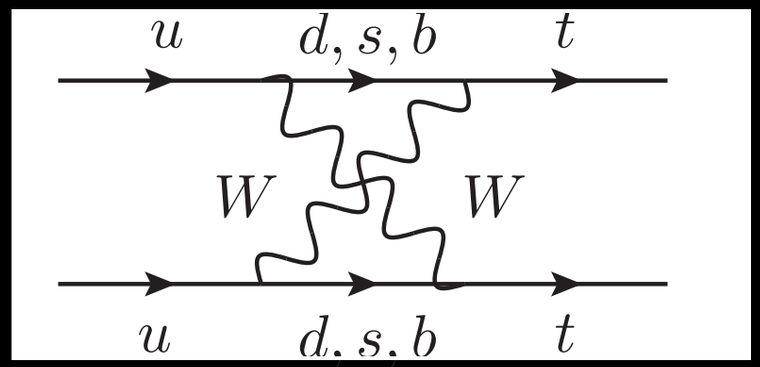
Same sign top pair production

- Almost no SM contribution



$$\propto m_b^2 {V_{ub}}^2$$

$$|M|^2 \approx 0^2 + 2\Re\left(0 M^*_{dim6}\right) + |M_{dim6}|^2 + \mathcal{O}\left(\Lambda^{-6}\right)$$

$$\begin{aligned}
\mathcal{O}_{RR} &= [\bar{t}_R \gamma^\mu u_R]\,[\bar{t}_R \gamma_\mu u_R] \\
\mathcal{O}^{(1)}_{LL} &= [\bar{Q}_L \gamma^\mu q_L]\,[\bar{Q}_L \gamma_\mu q_L] \\
\mathcal{O}^{(3)}_{LL} &= [\bar{Q}_L \gamma^\mu \sigma^a q_L]\,[\bar{Q}_L \gamma_\mu \sigma^a q_L] \\
\mathcal{O}^{(1)}_{LR} &= [\bar{Q}_L \gamma^\mu q_L]\,[\bar{t}_R \gamma_\mu\, u_R] \\
\mathcal{O}^{(8)}_{LR} &= [\bar{Q}_L \gamma^\mu T^A q_L]\,[\bar{t}_R \gamma_\mu\, T^A u_R]
\end{aligned}$$

$$\Delta F = 2 \neq \Delta F = 0$$

$$\left|c^{(1)}_{LL} + c^{(3)}_{LL}\right| \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 < 2.1\,10^{-4}$$

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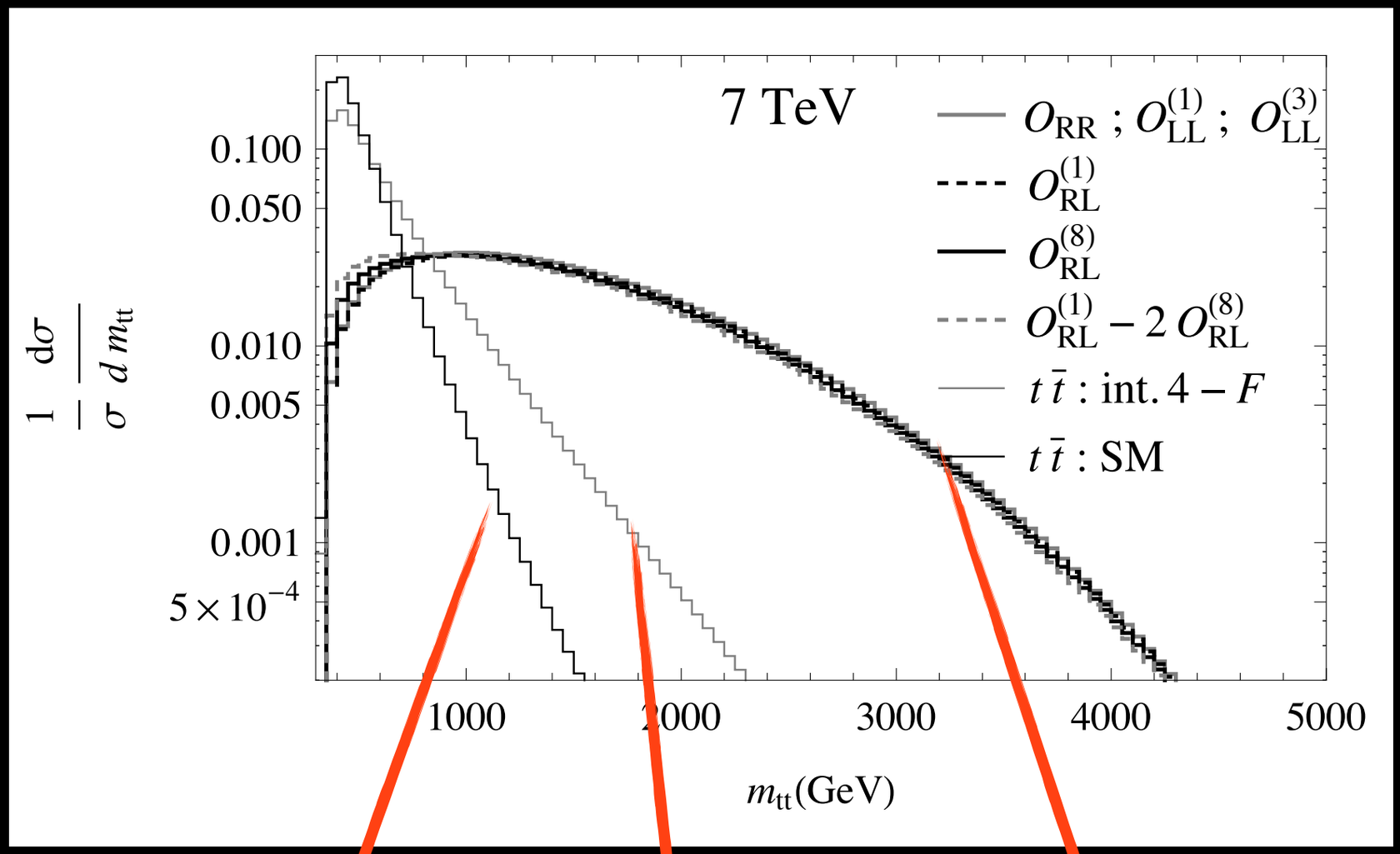
Invariant mass



EFT is only valid at low energies but a large contribution comes from the high energy region

$\sigma \propto 1/s$ $\sigma \propto 1/\Lambda^2$ $\sigma \propto s/\Lambda^4$

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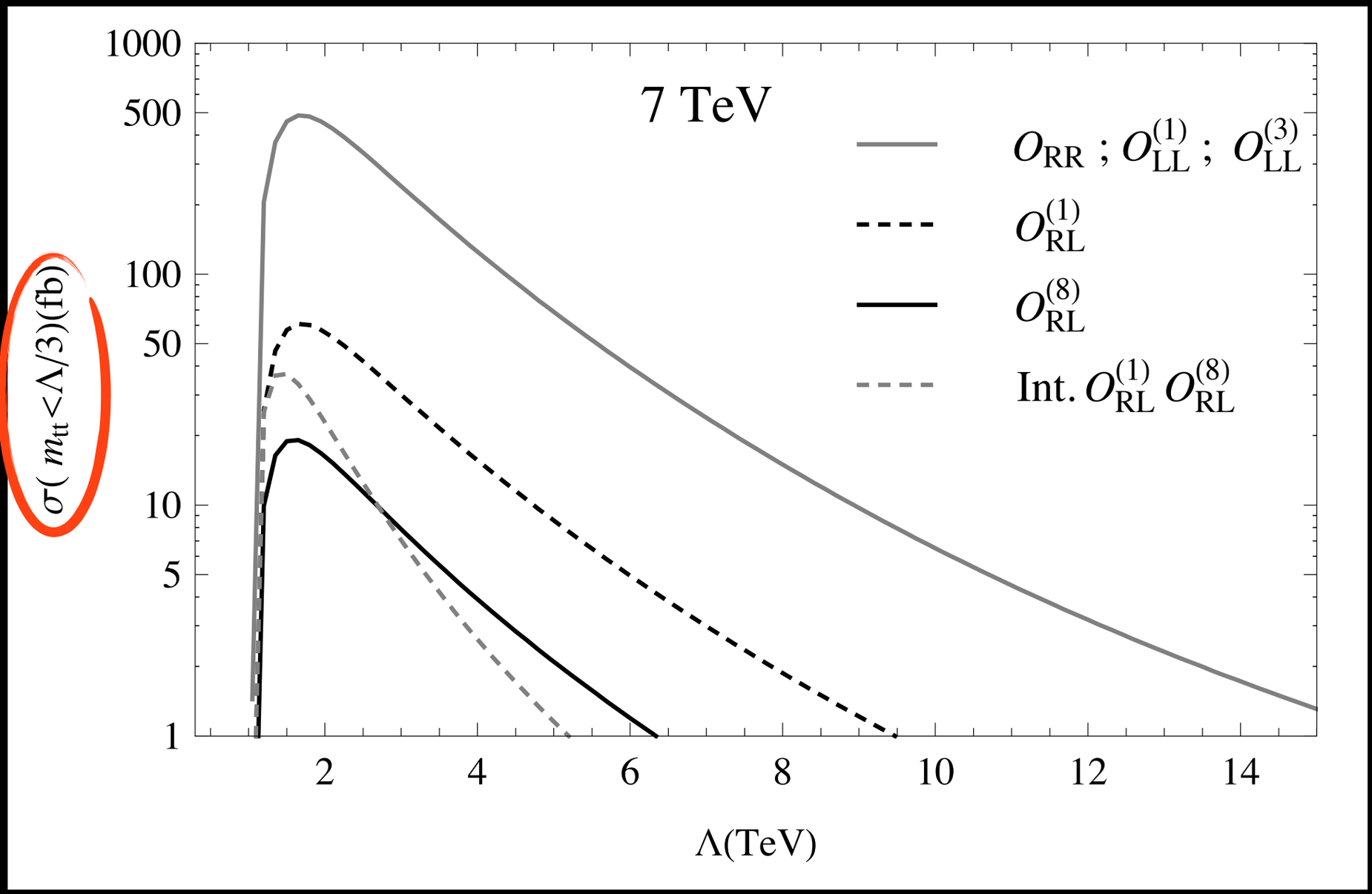
Cross-section



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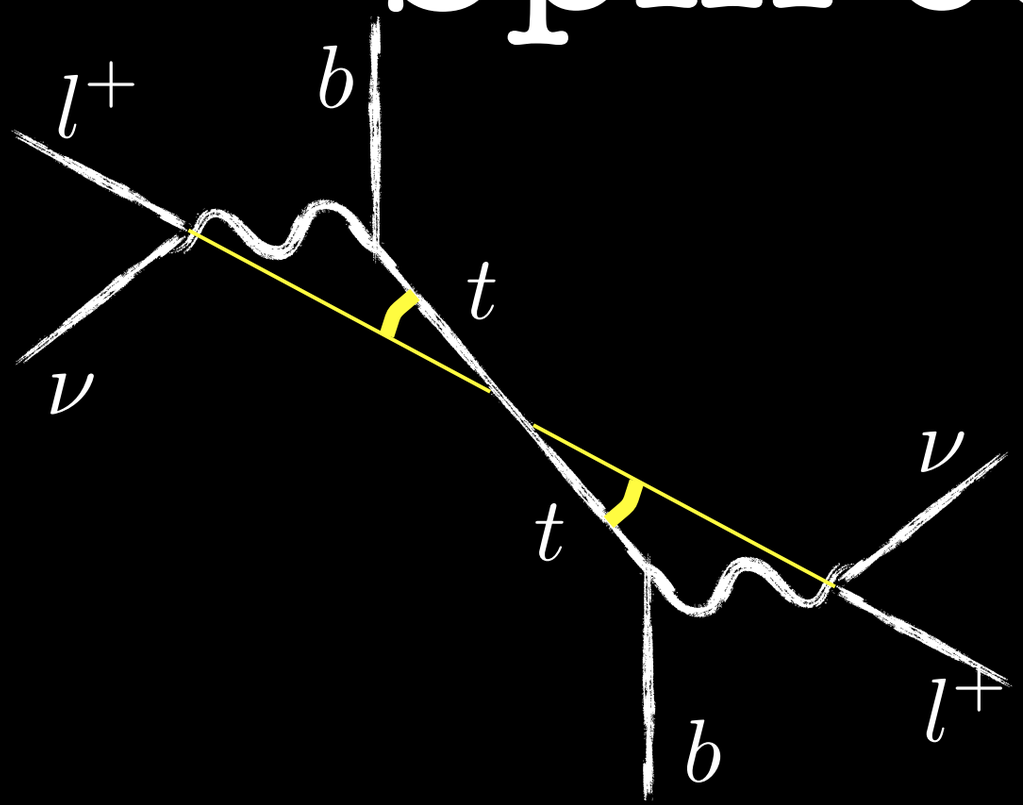
Spin correlations



$$C = \frac{1}{\sigma}\left(\sigma_{RR} + \sigma_{LL} - \sigma_{LR} - \sigma_{RL}\right)$$

$$b = \frac{1}{\sigma}\left(\sigma_{RR} - \sigma_{LL}\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 + C\cos\theta_1\cos\theta_2 + b\left(\cos\theta_1 + \cos\theta_2\right)\right)$$

$$\mathcal{O}_{RR} \rightarrow \quad C = 1,\, b = 0.997$$

$$\mathcal{O}_{LL} \rightarrow \quad C \;\text{"}\;\; ,\, b \;\text{"}-\;\; .\;!$$

$$\mathcal{O}_{LR} \rightarrow \quad C \sim 1,\, b \sim 0$$

C. Degrande

Concluding remarks

- EFT is complementary to searches of new particles
- EFT is predictive = guide NP searches
  - Few operators have been neglected (small effects)
  - No new operators for single top
  - Common operators for other processes
- EFT is renormalizable